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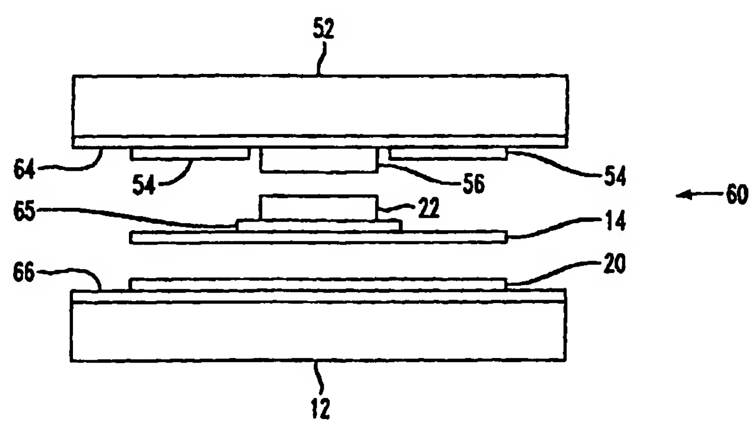
(54) Dual motion electrostatic actuator design for mems micro-relay

(57) A dual micro-electromechanical actuator for providing dual actuation to a micromachine. The actuator includes a first substrate upon which a first actuating electrode is formed. A second substrate located proximate to but spaced from the first substrate supports a second actuating electrode. A micromachine device, such as a thin membrane, plate or cantilever, is disposed between the actuating electrodes. When one of the actuating electrodes is selectively activated by applying a voltage thereto, an electrostatic attraction force is produced which causes movement of the micromachine in the direction of the activated actuating electrode.

FIG. 5



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Description

Field Of The Invention

[0001] The present invention relates to micro-electromechanical systems (MEMS) and, more particularly, to electrostatic actuation of MEMS devices in flip-chip bonded geometry.

Description Of The Related Art

[0002] Micro-electro-mechanical Systems (MEMS) have widespread uses in communications systems for performing, among other things, switching, relaying and wavelength routing functions. Electrostatic actuation is used to impart relative movement to thin membranes used in such devices. When thin membranes are brought into contact over a large area, the membranes tend to stick to each other due to surface-related attractive forces. Once this happens, it is difficult to separate the membranes due to the large surface-to-volume ratio, and the flexibility of the thin membranes. In surface micromachined devices where the mechanical devices are typically thin plates of structural materials like poly-crystalline silicon, this phenomenon is referred to as stiction. Since electrostatic actuation can only provide an attractive force, it is usually impossible to recover, e.g. to reset a device, once a micromachine sticks to the substrate. The only known way to recover is to mechanically detach the micromachine from the substrate with a needle probe.

[0003] Known MEMS relay devices use electrostatic actuation for moving two membranes into contact with each other to establish an electrical connection. Typical relays depend on mechanical restoration or spring forces to separate the two surfaces when electrical isolation between the two surfaces is necessary. For example, a known MEMS device 10 is shown in FIG. 1. The device includes a substrate 12 and a mobile micromachine, such as a cantilever 14 having a movable end 18 and a fixed end 16 secured to substrate 12. The cantilever 14 is controlled by an actuating electrode plate 20 which provides an electrostatic pulling force on cantilever 14 for moving edge 18 downward to substrate 12 when a voltage is applied between the cantilever 14 and the actuating electrode 20. A contact electrode 22 is disposed underneath the cantilever 14 and serves as a switch contact for closing a switch when the cantilever end 18 is in a first position (an "on" condition) and for opening the switch when the cantilever end 18 is in a second position (an "off" condition). To maintain the device 10 in the on position, a voltage must be continuously applied to the actuation electrode. When the voltage is no longer applied, (i.e. the switch is to be turned off), spring force in the cantilever causes end 18 to return to the second position.

[0004] When two parallel metallic plates (e.g. membranes) of area A separated by a distance d are placed in a vacuum (or air), the capacitance C between the two plates is given by

$$C = \varepsilon_0 A/d,$$

where ε_0 is the electrical permitivity of the vacuum, in the limit $A \gg d^2$.When a voltage difference of V is applied between these two plates, there is an attractive force F of

$$F = -CV^2/d$$

that pulls the two plates toward each other. This force is widely used to actuate metallic micromachines, since it is very simple to implement and the force can conveniently be provided by application of a voltage. Furthermore, no power is dissipated as long as the micromachine is not moving, since no current actually flows through the device.

[0005] Although this actuation mechanism has many advantages, it suffers from a few limitations. The most significant is that it can only provide an attractive force, and the resulting motion is thus in or toward a single direction. Another limitation is that when the contact material wears, the surface attraction force tends to increase. At the same time, and in particular for the device depicted in FIG. 10, as the mechanical cantilever fatigues, the restorative force tends to decrease. The combined effect causes the micro-relay to stick, resulting in device operation failure. Such failures are common in many MEMS devices where stiction destroys the mobility of the mechanical parts.

Summary Of The Invention

[0006] A dual motion micro-electromechanical actuator is disclosed for imparting controlled motion in both first and second directions to a micromachine, such as a diaphragm or cantilever. The actuator includes a first substrate upon which a first actuating electrode is formed, and a second substrate spatially separated from the first substrate, upon which a second actuating electrode is formed. A micromachine is disposed between the first and second actuating electrodes. When one of the actuation electrodes is selectively activated, such as by the application of a voltage, an electrostatic attraction force is produced between the micromachine and the activated electrode for moving the micromachine in the direction of the activated electrode, i.e. toward either the first substrate or the second substrate.

[0007] Such actuation mechanism can be used in a

MEMS relay. In a preferred embodiment of the relay, the micromachine is configured as a cantilever having one end fixed to the first substrate, with the other end moveable between the first and second substrates. A pair of contact electrodes are also included. One of the contact electrodes is supported by the second substrate and the other contact electrode is supported by the micromachine. When the micromachine is moved toward the second substrate, electrical contact occurs between the contact electrodes, and when the micromachine is moved toward the first substrate, electrical contact is broken between the contact electrodes.

[0008] Other objects and features of the present invention will become apparent from the following detailed description considered in conjunction with the accompanying drawings. It is to be understood, however, that the drawings are designed solely for purposes of illustration and not as a definition of the limits of the invention, for which reference should be made to the appended claims.

Brief Description Of The Drawings

[0009] In the drawings, wherein like reference numerals denote similar elements throughout the views:

FIG. 1 is a schematic representation of a prior art micro-electromechanical relay.

FIG. 2 depicts a dual electrostatic actuator in accordance with the present invention;

FIGs. 3a and 3b are schematic representations of the portions of a dual actuator section for use with a presently preferred embodiment of the present invention;

FIG. 4 schematically illustrates a dual actuator micro-electromechanical relay in accordance with a preferred embodiment of the present invention;

FIG. 5 is a cross-sectional view of the device of FIG. 4 taken along the line A--A' thereof; and

FIG. 6 is a cross-sectional view of the device of FIG. 4 taken along the line B--B' thereof.

Detailed Description Of The Currently Preferred Embodiments

[0010] With reference now to FIG. 2, the general concept of the inventive dual electrostatic actuator is demonstrated by an arrangement that includes three spaced-apart and parallel arranged conduction plates, namely an upper actuation electrode plate 42, a lower actuation electrode plate 44 and a middle electrode plate 46. The upper and lower electrode plates are attached to separate substrates (not shown) and the middle plate is mechanically mobile relative to the top and bottom plates. The middle plate is referred to as a micromachine and may be configured, for example, as a diaphragm, a cantilever, or other movable type component. A first voltage source applies a voltage V_1 between the top plate 42 and micromachine 46 and a second voltage source applies a voltage V_2 between the bottom plate 44 and micromachine 46.

[0011] To impart motion to micromachine 46 in an upward (in the drawing) direction toward upper plate 42, a positive (or negative) voltage V_1 is applied while V_2 is 0. To move the micromachine 46 in the illustrated downward direction toward lower plate 44, a positive (or negative) voltage is applied for V_2 while voltage V_1 is 0. In this manner, a positive actuation force may be imparted to the micromachine in either selected direction (upward or downward) depending on the desired direction of movement thereof.

[0012] In the preferred embodiment, the sizes of the plates 42, 44 and 46 range from about 1 to 10,000 microns per side, with a thickness of between about 0.01 to 10 microns. The spacing between the plates is between about 0.5 and 500 microns. In this range, the values for the voltages V_1 and V_2 are between about 0.1 and 500 V.

[0013] FIGs. 3a and 3b show a presently preferred embodiment of a MEMS relay. The device, like the prior art of FIG. 1, includes a substrate 12 and a movable micromachine, such as a cantilever 14 having a movable end 18 and a fixed end 16 secured to substrate 12. The cantilever 14 is controlled by an actuating electrode plate 20 which provides an electrostatic pulling force on cantilever 14 for moving edge 18 downward to substrate 12 when a voltage is applied between the cantilever 14 and the actuating electrode 20. A contact electrode 22 is disposed on the cantilever 14 and serves as a switch contact. A second actuator section 50 for use with the single actuator 10 of FIG. 3a is depicted in FIG. 3b and includes a second substrate 52, a second actuating electrode 54 and a second contact electrode 56 having an electrode head 58. The second activating electrode functions as the upper plate 42 of FIG. 2 in that when a voltage is applied, a mobile micromachine 14 disposed in proximity to the second actuating electrode 54 will undergo an electrostatic pulling force. When the second actuator section 50 is combined with the single actuator 10 of FIG. 3a, a dual actuator device 60 is formed, as shown in FIGs. 4-6. For ease of illustration, second substrate 52 is not depicted in FIG. 4.

[0014] The dual actuator device 60 is a mechanical relay employing a cantilever 14 as the mobile micromachine actuating member. The cantilever may be fabricated of a conductive material or of an insulating material upon which a conductive material is deposited. End 16 of cantilever 14 is fixed to the lower substrate 12 and the first actuating electrode is disposed between the lower substrate and the cantilever. A contact electrode 22 is formed on the cantilever for functioning, in

this particular described embodiment, as a section of a relay switch. As explained above, when a voltage is applied to actuating electrode 20, an attraction force is produced for causing cantilever 14 to pivot about fixed end 16 so that moving end 18 is pulled down toward lower substrate 12.

[0015] The additional actuator section 50 and, in particular, the second actuating electrode 54 having second contact electrode 56 disposed thereon, is spatially disposed above cantilever 14 as shown in FIG. 4. To cause electrical connection between the contact electrodes 22, 56, a positive voltage is applied between actuating electrode 54 and the movable cantilever 14 which responsively generates an attraction electrostatic force for pulling cantilever 14 toward second substrate 52. This, in turn, causes contact electrode 22 disposed on cantilever 14 to become electrically connected to contact electrode 56 without relying on an inherent spring force of the cantilever 14. To maintain electrical contact, a positive voltage will continue to be applied to second actuating electrode 54. When electrical contact between electrodes 22 and 56 is thereafter no longer desired, the voltage will no longer be applied to second actuating electrode 54 but will, instead, be applied between first actuating electrode 20 and the movable cantilever 14 for causing cantilever 14 to move toward the first substrate 12, thereby causing physical separation between the contact electrodes 22, 56.

[0016] Another desired characteristic for a relay is the high open-state maximum voltage characteristic. This is the voltage that can be applied across the contact electrodes of the relay when the switch is open, without changing the relay status or damaging the relay itself. For electrostatic actuators, a voltage across the contact electrodes themselves can act as an actuation force, that is, a voltage applied between the two contact electrodes will pull the contact electrodes together and tend to close the switch. Therefore, any design optimization to reduce the actuation voltage will also, in general, decrease the open-state maximum voltage in electrostatically actuated MEMS relays. One added advantage of the inventive dual actuator design 60 is that the second actuation electrode 54 (used to actively open the switch) can be actively biased during the open state to counteract the force generated by large voltage difference across the contact electrodes. This effectively increases the open-state maximum voltage.

[0017] The preferred embodiment for the dual electrostatic actuator 60 utilizes a flip-chip bonded geometry. In this geometry, the lower actuation electrode 20 and the mobile micromachine 14 are fabricated on a single substrate (e.g., substrate 12) using surface micromachining technology, while the upper actuation electrode 54 is fabricated on second substrate 52. For proper operation, the upper actuation electrode 54 is to be assembled in an appropriate location with respect to the mobile micromachine 14 and the lower actuation electrode 20 by means of flip-chip bonding so that the produced electrostatic actuation force will be properly directed. Spacers (not shown) of accurate thickness can be disposed between the upper and lower substrates to control the gap or spacing between the mobile micromachine 14 and upper actuation electrode 54; the spacing or gap between the mobile micromachine 14 and upper actuation electrode 54 determines the amount of force produced by the upper actuation electrode for a given voltage.

[0018] To assure electrical isolation between the various conductive components, the preferred embodiment includes insulating layers 64, 65 and 66. The insulating layers are preferably formed of silicon dioxide or silicon nitride. As shown in FIGs. 5 and 6, insulating layer 64 electrically isolates second substrate 52 from second actuating electrode 54, insulating layer 65 electrically isolates cantilever 14 from contact electrode 22, and insulating layer 66 electrically isolates first substrate 12 from the first actuating electrode 20.

[0019] Also in the preferred embodiment, electrical shorting between the actuating electrodes 20, 54 and the mobile micromachine cantilever 14 should be avoided because the high voltages required for actuation can cause spark welding of delicate micromachined components. Electrical shorting can be avoided by imbedding the actuation electrodes under an insulating layer 68, 69, also preferably formed of silicon dioxide or silicon nitride, or by shaping the actuation electrodes in such a manner that any regions of contact between the actuator electrodes and the micromachine have a potential difference of zero.

[0020] Thus, while there have shown and described and pointed out fundamental novel features of the invention as applied to preferred embodiments thereof, it will be understood that various omissions and substitutions and changes in the form and details of the devices illustrated, and in their operation, may be made by those skilled in the art without departing from the spirit of the invention. For example, it is expressly intended that all combinations of those elements which perform substantially the same function in substantially the same way to achieve the same results are within the scope of the invention. Moreover, it should be recognized that structures and/or elements shown and/or described in connection with any disclosed form or embodiment of the invention may be incorporated in any other disclosed or described or suggested form or embodiment as a general matter of design choice. It is the intention, therefore, to be limited only as indicated by the scope of the claims appended hereto.

Claims

1. A dual micro-electromechanical actuator, comprising:

    a first substrate;

a first actuating electrode formed on said first substrate;

a second substrate spaced from said first substrate;

a second actuating electrode formed on said second substrate in spaced relation to said first electrode; and

a micromachine disposed between said first and said second actuating electrodes, said first actuating electrode imparting an electrostatic attraction force to said micromachine in response to a voltage selectively applied to said first actuating electrode for moving said micromachine to a first position in a direction toward said first substrate, and said second actuating electrode imparting an attraction force to said micromachine in response to a voltage selectively applied to said second actuating electrode for moving said micromachine to a second position in a direction toward said second substrate.

2. The dual micro-electromechanical actuator of claim 1, further comprising a first contact electrode supported by said micromachine and a second contact electrode supported by said second substrate, said micromachine causing electrical contact between said first and said second contact electrodes when moved to said second position, and causing electrical isolation between said first and said second contact electrodes when moved to said first position.

3. The dual micro-electromechanical actuator of claim 1, wherein said micromachine comprises a diaphragm.

4. The dual micro-electromechanical actuator of claim 1, wherein said micromachine comprises a cantilever having a fixed end supported by said first substrate and a moveable end moveable between said first and said second positions.

5. The dual micro-electromechanical actuator of claim 2, wherein said micromachine comprises a cantilever having a fixed end supported by said first substrate and a moveable end moveable between said first and said second positions.

6. The dual micro-electromechanical actuator of claim 1, further comprising an insulating material disposed between said first substrate and said first actuating electrode, and between said second substrate and said second actuating electrode.

7. The dual micro-electromechanical actuator of claim 2, further comprising an insulating material disposed between said first substrate and said first actuating electrode, between said second substrate and said second actuating electrode, and between said micromachine and said first contact electrode.

8. The dual micro-electromechanical actuator of claim 1, further comprising means for preventing direct physical contact between said micromachine and said first actuating electrode, and between said micromachine and said second actuating electrode.

9. The dual micro-electromechanical actuator of claim 8, wherein said preventing means comprises an insulating material disposed between said micromachine and said first actuating electrode, and between said micromachine and said second actuating electrode.

10. The dual micro-electromechanical actuator of claim 1, wherein said micromachine and said first actuating electrode are formed on said first substrate.

11. The dual micro-electromechanical actuator of claim 1, wherein said second actuating electrode and said second substrate are flip-chip bonded to said first substrate and said first actuating electrode.

FIG. 1
PRIOR ART

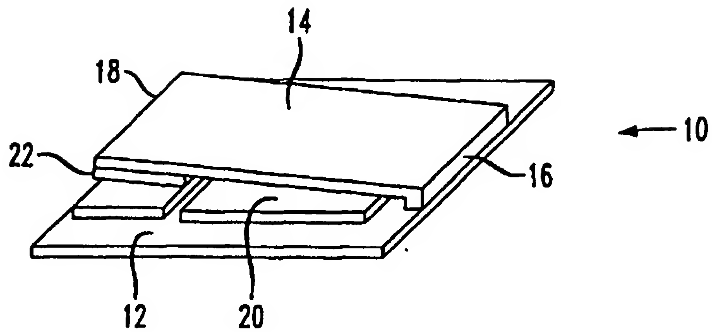

FIG. 2

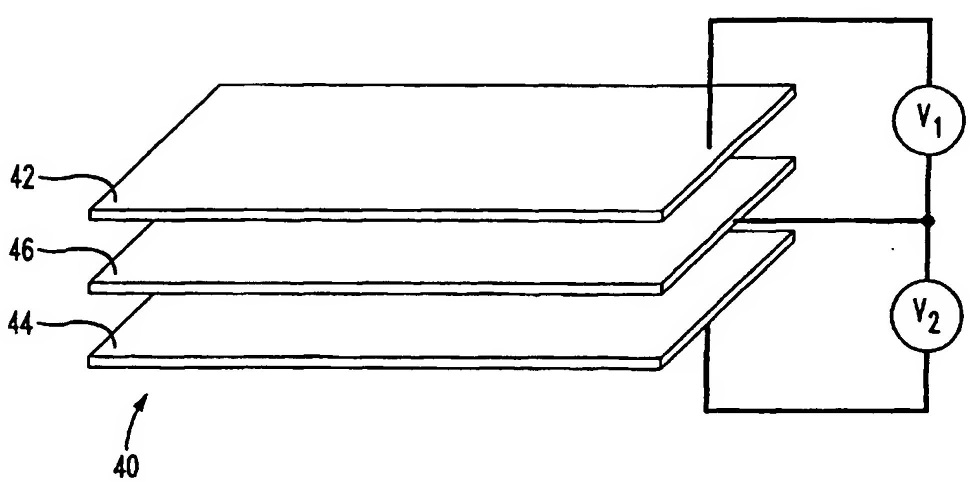

FIG. 3A

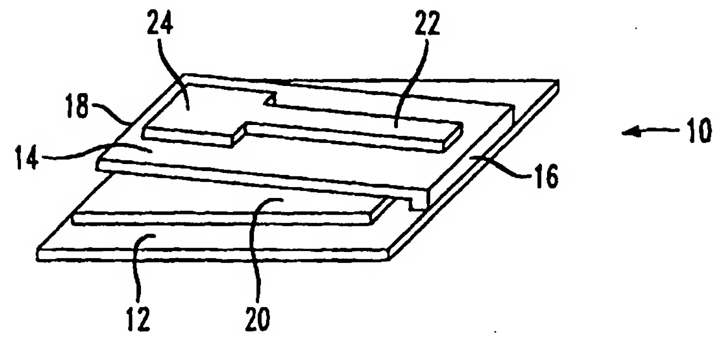

FIG. 3B

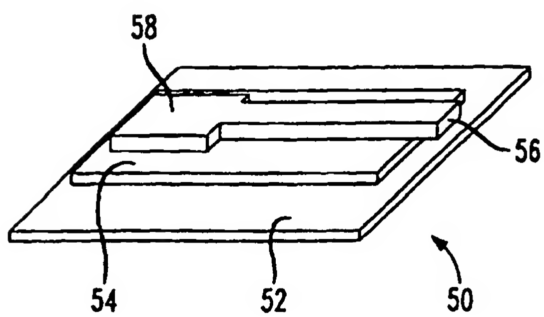

FIG. 4

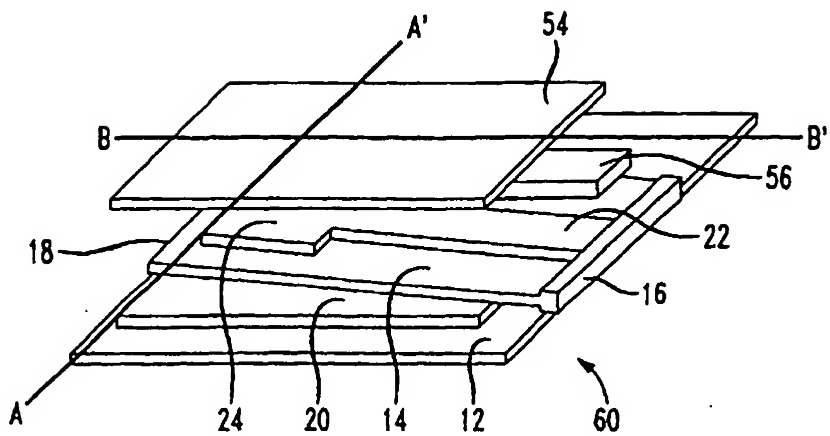

FIG. 5

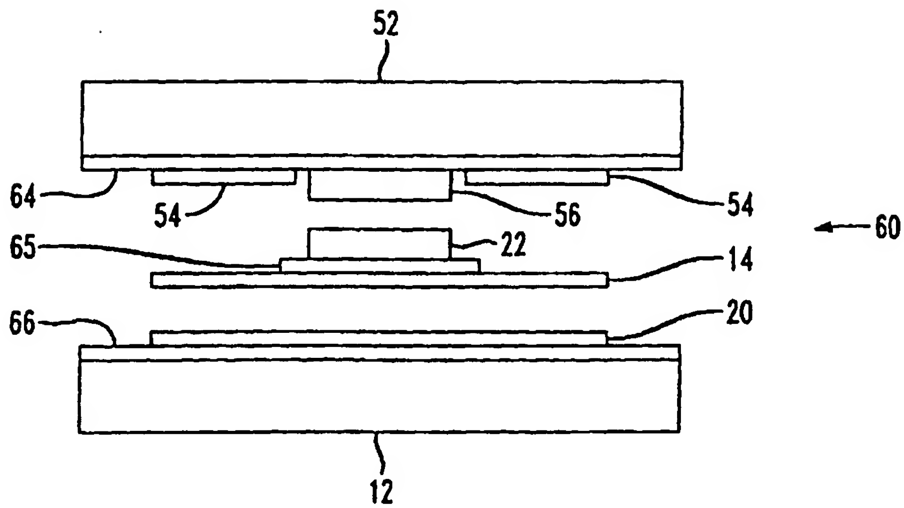
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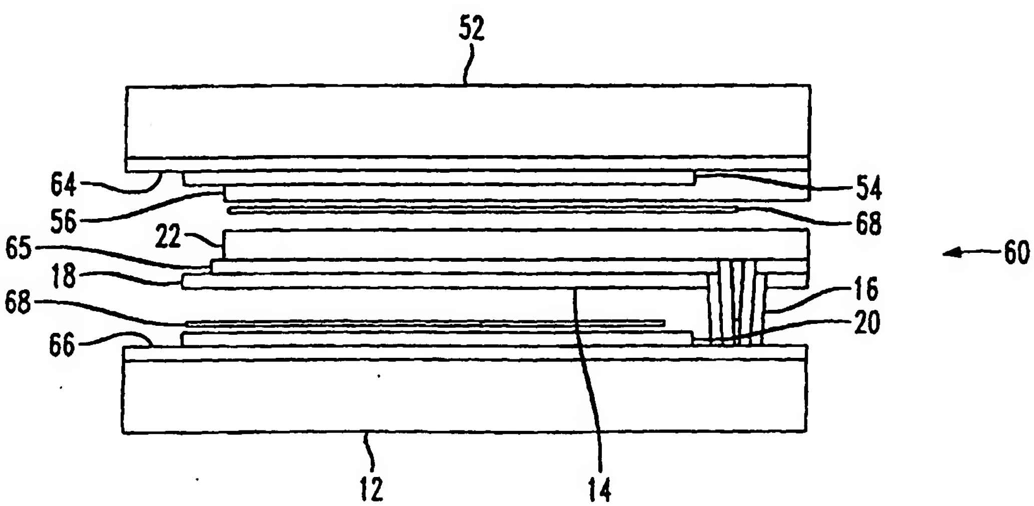
FIG. 6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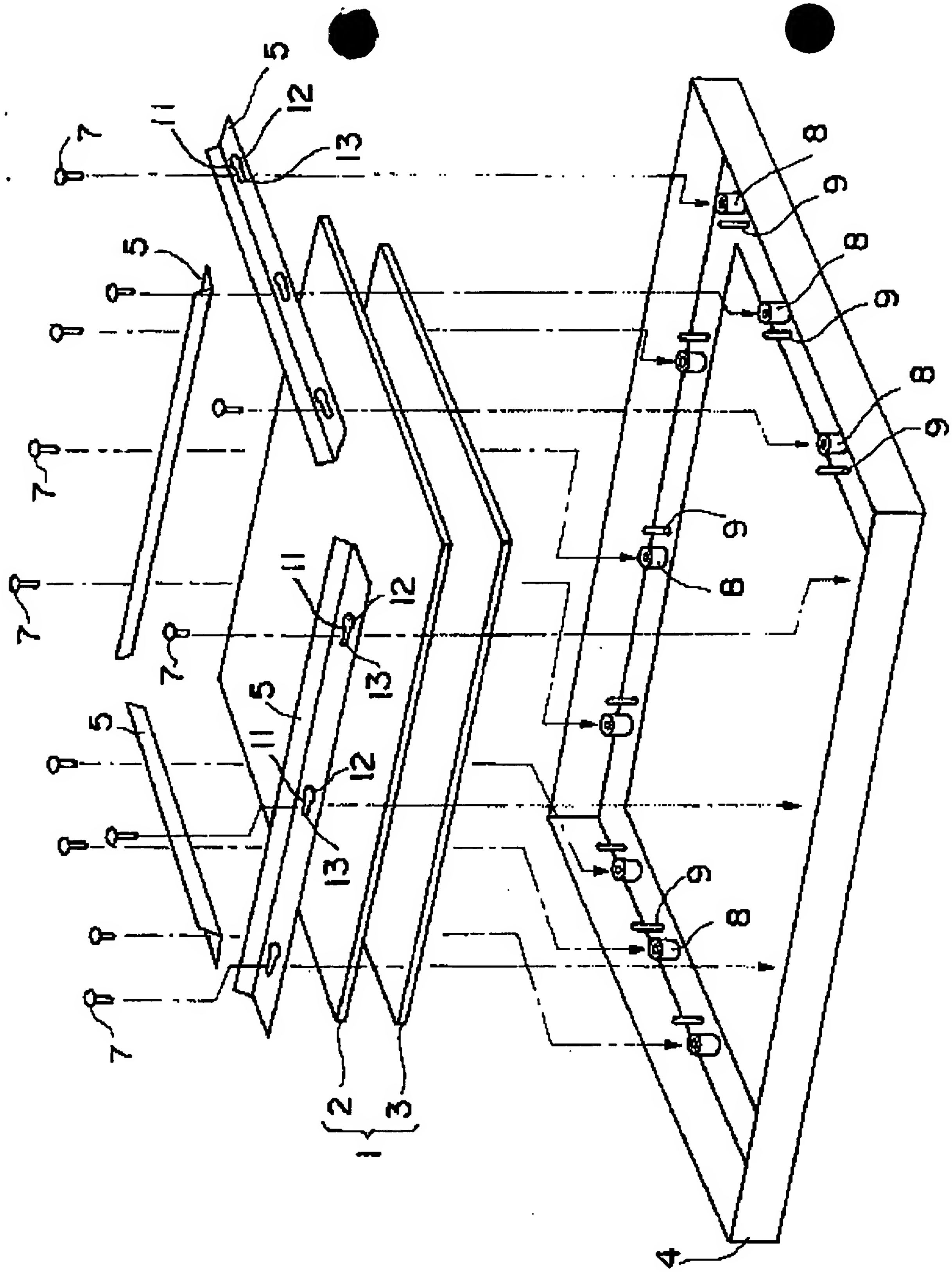
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